Metallurgy Department. Progress report for the period 1 January to 31 December 1973

Research Establishment Risø, Roskilde

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METALLURGY DEPARTMENT PROGRESS REPORT

for the Period 1 January to 31 December 1973

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INTRODUCTION

In 1973 the nuclear situation in Denmark changed considerably when a group of power companies (ELSAM) announced their intention to build a nuclear plant to be in operation by 1980. The Danish parliament and a number of organizations including Risø will participate in the licensing procedure, but besides this Risø will be involved in direct collaboration programmes with power companies and industry.

This change in the situation will, however, not drastically influence the programmes of the Metallurgy Department at Risø, which for many years has done extensive work within several areas of nuclear technology including the design and fabrication of fuel elements, in- and out- of-pile testing of nuclear materials and fuel elements, steel research, corrosion research, and non-destructive testing of nuclear components. As examples the department has in 1973:

- delivered four zircaloy-UO_2 fuel elements to the Kahl reactor (BWR) in Germany. These elements, about 300 kg of fuel, were manufactured in collaboration with The Elsinore Shipbuilding and Engineering Co., Ltd.;
- obtained a large contract from the CNEN/ENEL, Italy, for the examination of a number of Pu-containing fuel rods from a BWR power reactor;
- entered into a contract with The Elsinore Shipbuilding and Engineering Co., Ltd. for the production and sale of a non-destructive tube inspection system. Based on ultrasonic techniques, this system can control tube dimensions and inspect tube defects with a speed of about 6 metres of tubing per minute.

Although a large part of the department's effort has been devoted to nuclear projects, collaboration with Danish industrial companies on non-nuclear projects has been continued, especially in the fields of development of new materials, powder metallurgy, and joining methods. Two senior staff members have, on a part-time basis, acted as consultants to specific companies.

In the beginning of 1973 a large extension to the laboratory building was started. This extension, which is about 1000 m^2, will contain laboratories for powder metallurgy, corrosion, physical metallurgy, non-destructive testing, and brazing. The laboratories will be available to the department in March 1974.

General Materials Research

The work covered research into the irradiation, deformation, strength, and structure of single-phase and two-phase materials, fracture mechanics, and oxidation.

Irradiation effects in molybdenum were studied with the emphasis on void formation caused by low-temperature neutron irradiation followed by high-temperature annealing and, in particular, on the surprisingly high efficiency of this void formation process. Experimental investigations were made by positron annihilation (in collaboration with the Chemistry Department and with various laboratories at the Technical University of Denmark), and theoretical investigations were made by computer simulation.

The investigation of void volume swelling in stainless steel caused by irradiation in a high-voltage electron microscope was continued in collaboration with the AERE, Harwell. The "defect depletion model" for the grain size effect on the swelling was confirmed by further investigations including computer calculations of vacancy supersaturation profiles. The effects of temperature and dissolved gas content on the grain size effect and on irradiation induced grain boundary migration were also studied. (See article p. 12).

In an investigation of deformed sapphire (carried out together with the Department of Metallurgy and Materials Science, University of Oxford) the existence of dislocations with Burger vector $\langle 01\bar{1}0 \rangle$ lying on $\{11\bar{2}0\}$ prism planes was established. Weak beam electron microscopy indicated that these dislocations are dissociated into two partial dislocations (see fig. 1).

Neutron diffraction measurements of the texture of copper and brass rolled to 40% reduction combined with electron microscopy confirmed that mechanical twinning cannot account for the texture difference between the two materials: this is in agreement with a theory suggested for the plastic deformation of face-centred cubic polycrystals.

In the work with computer simulation of grain boundary structures (carried out in collaboration with the Department of Structural Properties of Materials at the Technical University of Denmark) the effects of variations in temperature and pressure were studied. Also, alternative ways of generating grain boundaries, excluding melting, were investigated.

Various fundamental aspects of the mechanical properties and microstructures of zirconium alloys were studied. The fracture voidage in hydrided zircaloy-2 was found to increase with increasing temperature and to exhibit a maximum at a certain strain rate. Dispersed particles (Y_2O_3) were found to suppress "post-irradiation softening", thereby increasing

the usable ductility. The properties of a Zr-Cr-Fe alloy were improved by a special duplex ageing treatment.

The mechanical properties of dispersion-strengthened copper alloys (Cu/Al_2O_3 and $Cu\text{-}Ag/Al_2O_3$) were investigated at room temperature with the emphasis on the additivity of various strengthening contributions (dispersed particles, solid solution atoms, grain boundaries); the work was performed in collaboration with the Department of Structural Properties of Materials at the Technical University of Denmark. In aluminium dispersion-strengthened with aluminium oxide the creep behaviour in the temperature range 300-600°C and the tensile behaviour in the temperature range -196-600°C were studied (together with the Batelle Memorial Institute, Columbus, Ohio). The high-temperature strength never went below one half of the Orowan stress, not even for very low creep rates.

Dispersed particles may, depending on various circumstances, ac-

Fig. 1. Weak-beam dark-field electron micrograph of a $[01\bar{1}0]$ edge dislocation in sapphire, taken in $\vec{g} = (03\bar{3}0)$ with Bragg angle corresponding to $-1.2\,\vec{g}$.

Fig. 2. Nucleation at $FeAl_3$ particle in aluminium cold-deformed 90% by drawing and annealed 1 hour at 260°C.

celerate or decelerate recrystallization. These effects were studied in Al/Al_2O_3 and Cu/Al_2O_3 by electron microscopy (in collaboration with the Danish Academy of Engineering). The interest was concentrated on the influence of the particles on the dislocation structure after cold working and on the nucleation of recrystallized grains near the particles (fig. 2).

In investigations of the mechanical properties of fibre composites copper reinforced with tungsten fibres was used as a model material. Data for the room temperature work-hardening rate of the matrix phase were analysed in terms of an influence of the size of fibre-free matrix areas similar to the influence of grain size in polycrystals. A mathematical model was developed for creep in fibre composites. The model explicitly includes the constraint effect of the fibres on the matrix.

The thermodynamical properties of uranium-plutonium oxides were measured in collaboration with the AB Atomenergi, Sweden.

The COD (crack opening displacement) method was applied in measurements of the fracture-mechanical properties of steel in the elastic/plastic range of deformation (in collaboration with Det Danske Staalvalseværk and the Danish Academy of Engineering). Measurements were made on various types of steel subjected to various annealing treatments. The "crack" was either an impressed knife notch or a fatigue crack.

From an investigation of the effect of intermetallic particles on the oxidation of zirconium alloys it was suggested that the transition is caused by the oxidation of these particles. The transport properties in hypostoichiometric zirconium oxide were studied. The results indicate that hydrogen diffuses as neutral atoms via anion vacancies.

Materials Development

The examination of several advanced zirconium alloys with respect to fabrication variables, mechanical properties, irradiation behaviour, and corrosion resistance was continued.

Work on zircaloy-2 dispersion strengthened with yttria was concentrated on attempts to improve the mechanical properties even further by using a wet-milling process during fabrication. It was established that the new process results in a more uniform distribution of the dispersed particles and a smaller final grain size than the old process. Improved strength properties, resulting from these microstructural changes, were achieved. Unfortunately the corrosion behaviour of the alloy is not at the moment satisfactory. A collaboration with the AECL in Canada was initiated; specimens of dispersion-strengthened zircaloy-2 were sent to the AECL who are to determine the in-pile creep behaviour of the material.

Fig. 3. Zr-2 a/o Cr-0.16 a/o Fe, solution heat-treated at 1050°C for ½ hour and then quenched into water. The microstructure shows twinned martensite plates contained in a Widmanstätten-α matrix.

The zirconium alloys investigated in collaboration with the UKAEA, AB Atomenergi, Sweden, IFA, Norway and the Finnish AEC, continue to show promise. The mechanical properties of the alloys in the temperature range 25-400°C were determined. In the temperature range 250-400°C the alloys have strengths better than or equal to zircaloy-2 and the decrease in their strengths with increasing temperature is significantly less than for zircaloy-2. Minipins of the alloys were irradiated in the DR 3. Preliminary results from post-irradiation examinations show that, qualitatively, several of the alloys have an in-pile corrosion resistance similar to that of zircaloy-2. Quantitative data on the in-pile corrosion behaviour are currently being obtained, using the in-pile corrosion loop facility.

A method for transforming the scale from steel production into iron powder was perfected. The resulting powder has properties comparable to those of commercially produced powders. An economic evaluation of the process is now being made.

In collaboration with the Danish Welding Institute, steel weld seams of preselected composition were successfully produced by the electro-slag forming process, using electrodes supplied by the ESAB.

As part of a NORDFORSK project the development of composite alloys of nickel reinforced with tungsten fibres was continued. A potential use for the alloys is in gas turbines; the higher operating temperature possible with these alloys would lead to greater efficiency. During the past year the production techniques for the alloys was improved by more accurate controlling of the process operating temperature. Series of specimens produced by the improved technique were subjected to tensile and creep deformation. The production of composites with nickel alloys rather than pure nickel as the matrix was also initiated.

Other work in the field of composite materials was performed in collaboration with the Chemistry Department and the Meteorology Group. A composite of carbon fibres in plastic was used for the production of anemometer cups; tests conducted on these new cups gave excellent results.

In order to obtain experience of the influence of various process parameters on the anodizing of aluminium, a number of aluminium plate specimens were anodized. Both the corrosion behaviour in NaCl solution and the hardness of the anodized specimens were tested.

The permeability of hydrogen, through supported and unsupported membranes of a Pd-B alloy, at high temperatures and a hydrogen pressure differential of 1 atmosphere, was investigated. For supported membranes very little reaction was found between the membrane and the support material even at 700°C.

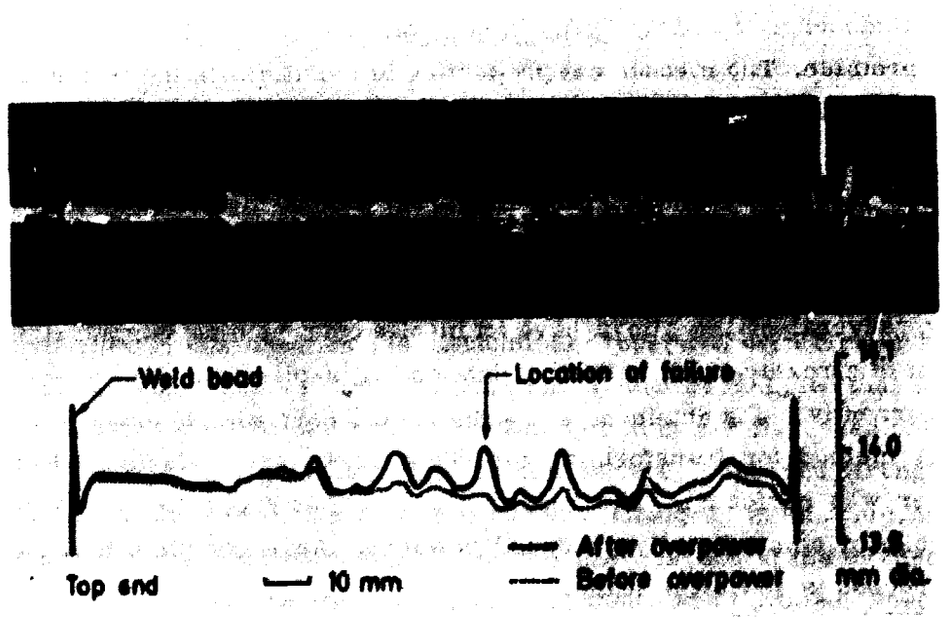

Fig. 4. Diameter change along fuel pin subjected to overpower test.

Fuel Elements

The six Danish UO_2-zircaloy test fuel elements that are at present being irradiated in the Halden BWR, Norway had, by the end of December 1973, achieved average burn-ups ranging from 10,200 to 27,200 MWD/t UO_2. The highest local burn-up, namely 34,000 MWD/t UO_2, was obtained in the IFA 161.

Analysis of one of the unloaded assemblies, IFA 162, showed that there is little difference between the thickness of the oxide layers on unautoclaved and autoclaved pins. The pellet stack shortening and the pin elongation found in the IFA 162 assembly has been explained by a model based on a ratcheting pellet movement resulting from mechanical fuel - cladding interaction during successive irradiation periods. Metallographic examination of the inside of the cladding revealed systematic patterns of marks from pellet cracks and interfaces which gave support to the model.

The maximum burn-up of the UO_2-Zr test fuel pins being irradiated at nominal BWR conditions (70 atm, 285°C) in the DR 3 reactor has reached 35,300 MWD/t UO_2. Overpower tests were carried out on fuel pins with burn-ups exceeding 20,000 MWD/t UO_2. One pin exhibiting the most severe combination of design and operating parameters (small pellet - clad clearance, long pellets, high heat load) failed when its heat load was raised from 350 to 420 W/cm over a period of about two minutes. The diameter change during the overpower test is illustrated in fig. 4.

Irradiations of UO_2-Zr test fuel pins under PWR conditions and of PuO_2-UO_2-Zr pins under BWR conditions were performed during the year in the DR 3 reactor. The last-mentioned pins were produced in co-operation with the AB Atomenergi, Studsvik, Sweden.

Four UO_2-Zr fuel elements were produced for delivery as "partial reload" to the German Kahl reactor. The elements will be inserted in the reactor in the scheduled shut-down in 1974. The average burn-up is estimated to reach 18,000 MWD/t UO_2 over a period of 6 years with a maximum local burn-up of 31,000 MWD/t UO_2.

Performance models were developed to simulate mechanical interaction between UO_2 pellets and clad. Pellet radial cracking, ridge formation, and irradiation creep of both UO_2 and zircaloy are included together with longitudinal interaction effects.

The development work on methods for the fabrication of U-Al tubular elements was continued. The work was mainly concentrated on methods for the welding of plates to tubes and the subsequent calibration of these tubes. The first element is scheduled to be inserted in the DR 3 reactor in the spring of 1974.

The in-pile heat conductivity rig No. 2 has been examined in the Hot Cells and the results are now being evaluated. The equipment for post-irradiation examination of fuel elements was supplemented with Ge-Li detector equipment for advanced spectrometry and an eddy current test unit for non-destructive detection of cladding defects.

After promising results from preliminary experiments on the use of the DR 1 reactor as a neutron source for neutron radiography of irradiated fuel pins, a permanent shielding was constructed for pins of a length up to 2 metres. The construction of six lead-shielded glove boxes in the Hot Cells is almost completed.

Materials Technology

The work was concentrated on improvement of the fabrication techniques for fuel elements.

A new brazing process was developed for joining Inconel 718 and X-750 materials used in the fabrication of fuel spacers. By introducing a getter material around the brazing zone it is possible to reduce the brazing temperature or to use a poorer vacuum. Perfect wetting and filling characteristics with contact angles of less than 5^{o} were obtained at 1000^{o}C and 10^{-5} mm Hg, and also at 1025^{o}C and 10^{-2} mm Hg. A lower brazing temperature lowers the penetration of the nickel-based brazing filler materials

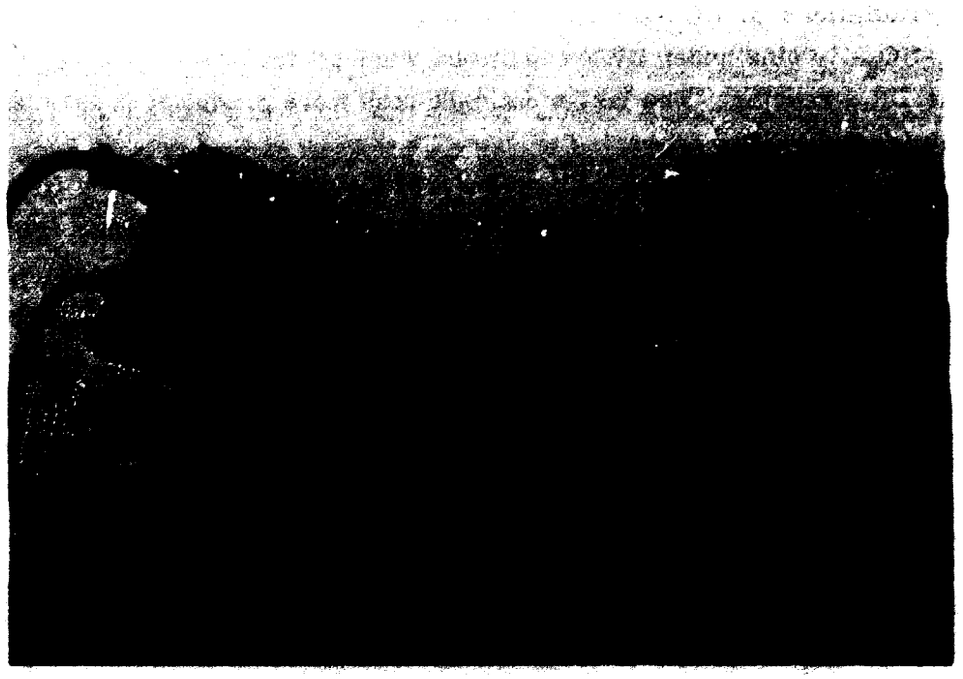

Fig. 5. Equipment for ultrasonic soldering. Two generators produce ultrasonic vibrations in the bath of liquid solder metal.

and hence improves corrosion resistance under reactor operating conditions. Furthermore the use of a getter material replaces the difficult elimination of the surface oxides before brazing.

The application of ultrasonic equipment for soldering was investigated. The ultrasonic energy is converted into mechanical energy in the liquid solder metal and results in a cavitation phenomenon in the bath. By means of this cavitation the oxide layer is removed from the surface of work pieces, thus allowing the solder metal to wet the base metal. Because flux agents are avoided a better corrosion resistance is obtained. The technique proved very useful for the joining of aluminium parts.

Welding under high pressure is used during the sealing of fuel pins for PWR's, and for this purpose a special apparatus was developed. A TIG weld electrode was built into a specially designed pressure unit which fits the end plug of a fuel pin. Before welding of the pin takes place, an evacuation and pressurization cycle is repeated a number of times.

A procedure for butt-joining aluminium sheets was established which gives a very uniform joint and a rather narrow heat-affected zone. The new jig construction allows welding of both flat and curved plates.

Experiments on accelerator radiography were continued. Various X-ray film and intensifying screen combinations were tested and exposure charts calculated.

The tube inspection system was upgraded from laboratory equipment to industrial prototype. This involved several changes both in mechanical parts and electronic signal handling. (See article, p. 17).

VOID FORMATION IN AN "EXPERIMENTAL" AUSTENITIC STAINLESS STEEL DURING HIGH-ENERGY ELECTRON IRRADIATION

B. N. Singh

During irradiation, when energetic particles of energy greater than the displacement energy collide with lattice atoms, the atoms are permanently displaced from their original lattice sites, creating vacancies and self-interstitial atoms. Under thermal activation these lattice defects migrate in the crystal. While migrating, most vacancies and self-interstitials either recombine with each other or annihilate themselves at internal sinks (i. e. dislocations, grain boundaries, interfaces) and at external sinks (i. e. surfaces). However, because of strain field interaction between dislocations and self-interstitials, the latter are attracted preferentially to the dislocations, leaving a supersaturation (i. e. an excess) of vacancies in the crystal. These excess vacancies precipitate as small vacancy clusters which in the presence of gas atoms become three-dimensional voids. These voids then grow during the subsequent irradiation as long as a supersaturation of vacancies is maintained. This can cause an overall volume increase of the material by several per cent. This, in turn, poses a serious problem for material scientists and engineers concerned with the development of fast breeder reactors.

It is now well established that structural parameters such as dislocations, grain boundaries, precipitates, particles, and foreign atoms play an important role in determining the irradiation-induced swelling behaviour of metals and alloys. We used our experimental stainless steel to study the effect of grain size and dispersed particles on void volume swelling during electron irradiation.

Extruded bars and hot-rolled sheets of our experimental stainless steel, with and without a dispersion of second-phase particles (RMS-2 and RMS-1, respectively) were fabricated from pre-alloyed powder of the composition quoted in table 1; aluminium oxide particles were used as the dispersoid.

Table 1

Composition of pre-alloyed powder

Element	Fe	Ni	Cr	C	Mo	Nb	W	Si
Concentration (w/o)	Bal.	20	20	0.02	ND[x]	ND[x]	ND[x]	0.22

[x] not detectable

Prior to irradiation specimens were annealed in a vacuum of 10^{-6} torr at 800°C or 1150°C for 2 hours. Thin films were prepared from the annealed samples by electropolishing at -20°C in ethanol containing 20 v/o perchloric acid.

Fig. 6. Formation and growth of voids in a thin foil during 1 MeV electron irradiation.

In some thin films 10 ppm of helium was implanted at room temperature, using a 100 kV heavy ion accelerator. Thin films both with and without helium were irradiated at 1 MeV in the EM-7 electron microscope (HVEM) at Harwell; all irradiation experiments mentioned here were made at 600°C. During irradiation a vacuum of ~2-3 x 10^{-7} torr was maintained around the specimen. The microscope current was adjusted to give a dis-

placement rate (ϕ) of 5.16×10^{-3} dpa sec^{-1} (displacements per atom per second) within a 0.5 μm diameter circular area on the specimen. The thickness of the layer within the foil which contained voids was measured from stereo pairs of micrographs, using a stereomicroscope. For comparison, a specimen of cast and solution-treated (at 1150°C for 30 min) AISI type 316 stainless steel was also irradiated under exactly the same conditions as our RMS-1 and RMS-2 stainless steels; the average grain size of the 316 stainless-steel specimen was of the order of 50 μm. The size of the grains irradiated in RMS-1 and RMS-2 samples varied between 0.45 and 2.77 μm.

The effects of grain refinement and a dispersion of second-phase particles on void formation and void volume swelling are highlighted by the following results:

(a) Void Nucleation

There are two significant aspects of our observations which can be related to the effect of grain size on the nucleation of voids. Firstly, our results show that the dose at the point when voids reach a clearly resolvable size increases with decreasing size of the irradiated grain. Secondly, at any dose level, the void number density in the centre of the grain under irradiation decreases markedly with decreasing grain size.

(b) Void Growth

We generally observe that the void growth rate, particularly at lower doses, decreases slightly with decreasing grain size. The growth rate behaviour is, however, complicated by the fact that it is also a function of the void number density. The influence of grain size on void growth is not as strong as its influence on void number density. This would suggest that the grain size effect is nucleation controlled.

(c) Void Volume Swelling

The void volume swelling, $\Delta v/v$, measured in the centre of grains of various sizes, clearly indicated that swelling is less the smaller the siz : of the irradiated grain. We should note here that for a given grain size, void volume swelling was markedly smaller in dispersed than in undispersed samples. The incoherent interfaces between the aluminium oxide particles and the stainless-steel matrix are expected to act as non-preferential and effective sinks for both vacancies and self-interstitials. However, when as sinks it is very difficult to analyse the role of these interfaces in reducing the voidage level in the grain interiors.
these particles are situated at the grain boundaries which themselves act

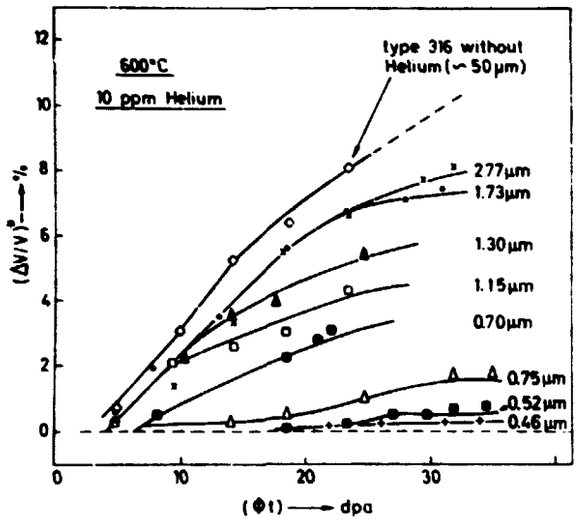

Fig. 7. Variation of $(\Delta V/V)^*$ with dose for grains of various sizes.
RMS-1: X ● ▲ □ ■
RMS-2: Δ ■ +

Void Denuded Zone and its Effect

It is a very common observation that void denuded zones are formed along grain boundaries. The void volume swelling measured in the centre of a grain is therefore not representative of the swelling of the bulk material. From a simple geometrical consideration of a spherical grain of diameter d_g containing a denuded zone of width W_D it can be shown that

$$(\Delta v/v)^* = (\Delta v/v)\left[\frac{d_g - 2W_D}{d_g}\right]^3 , \qquad (1)$$

where $(\Delta v/v)^*$ is the representative swelling for the whole grain including the denuded zone. Using the measured values of $(\Delta v/v)$ and W_D, the $(\Delta v/v)^*$ has been computed for different grains irradiated to various doses and the values are shown in fig. 7 which clearly demonstrates the effect of grain size on void volume swelling. A comparison of the grain size dependence of $\{(d_g - 2W_D)/d_g\}^3$ with that of the measured $(\Delta v/v)^*$ values shows[1] that the observed grain size effect is significantly greater than that expected from a simple geometrical consideration of the denuded zone outlined above.

Defect Depletion Model

The above-mentioned grain size dependent void formation and void volume swelling can be explained in terms of the loss of the irradiation

[1] B. N. Singh, Risø Report No. 287, 1973

induced point defects from the grain interiors to the grain boundaries. The explanation is based on the fact that grain boundaries act as neutral and unsaturable sinks for vacancies as well as for self-interstitial atoms. It is this property of the grain boundaries which leads to the formation of void denuded zones along the boundaries as mentioned above. We assume that the denuded zones thus produced contain vacancy concentration profiles originating from the grain boundaries and reaching their maximum at a distance $x \rangle W_D$ in the grain interior as illustrated schematically in fig. 8. In grains below a certain size these profiles are assumed to interact. Consequently the overall vacancy concentration or more importantly the vacancy supersaturation in the grain interior is reduced.

According to the model described above the smaller the grain (below a given size), the lower would be the vacancy supersaturation in the grain interior. The consequences of this prediction and its correlation with our results have been discussed in detail elsewhere[2]. In view of our results and the present model it seems that (a) the grain size effect is due mainly to the defect depletion from the grain interior, (b) the nucleation of voids is strongly influenced by the vacancy supersaturation level, and (c) the grain size effect is controlled predominantly by the nucleation process.

Calculation of Vacancy Concentration and Supersaturation Profiles

In order to test the above model we calculated the vacancy concentration and supersaturation profiles in three-dimensional spherical grains up to 3.0 μm in diameter. In our calculations the trapping of vacancies and interstitial atoms at the various sinks in the material (i.e. voids, dislocations) is represented by means of a continuum sink which is given by a trapping probability - comparable with that of the actual discrete sinks. We divide the strength of the equivalent continuum sink into two components: (i) the sink strength α_{void} ($= 4\pi r_v \cdot c_v$, where r_v = void radius and c_v = void number density) of the voids and any other neutral sinks and (ii) the sink strength α_{disl} ($= \rho d$ = dislocation density) of the dislocations, which are slightly biased (~1.0%) in favour of trapping interstitial atoms. We then calculate in detail the diffusional flow of the point defects to the grain boundaries, using the relevant data for austenitic stainless steel under electron irradiation at 600°C. The details of the calculations and their boundary conditions are described elsewhere[3].

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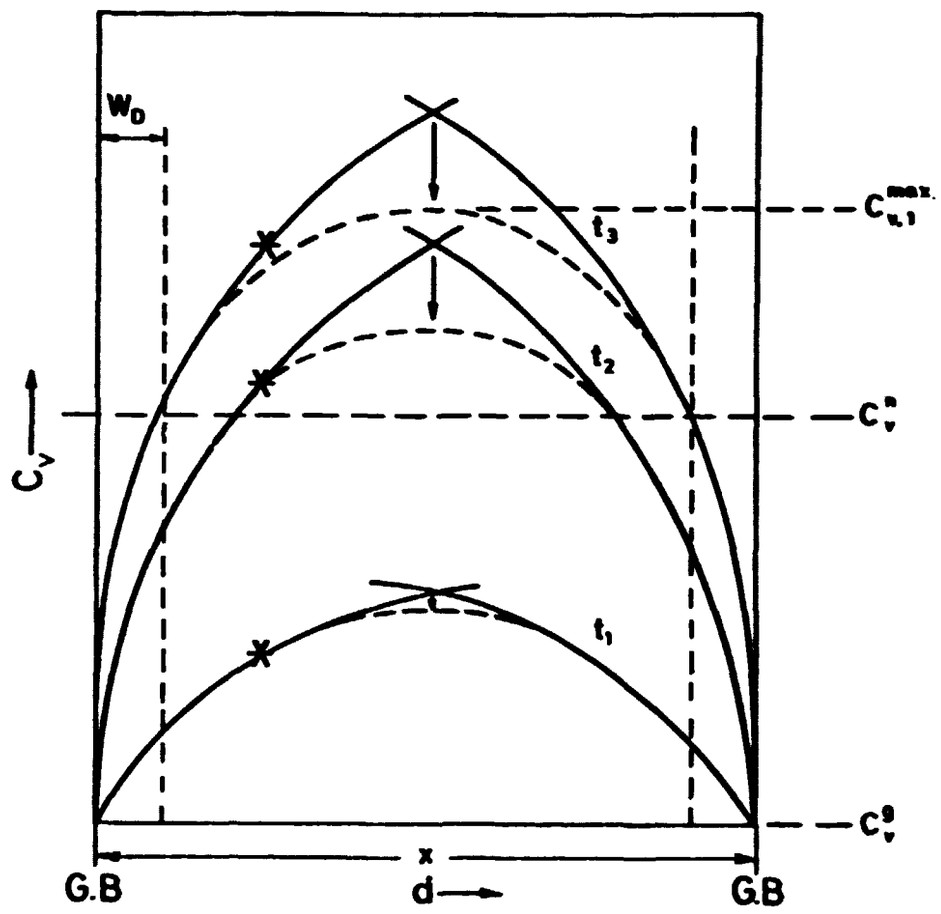
2) B. N. Singh, Phil. Mag., 29, 1974, p. 25

3) B. N. Singh and A. J. E. Foreman, Risø-M-1679, 1973



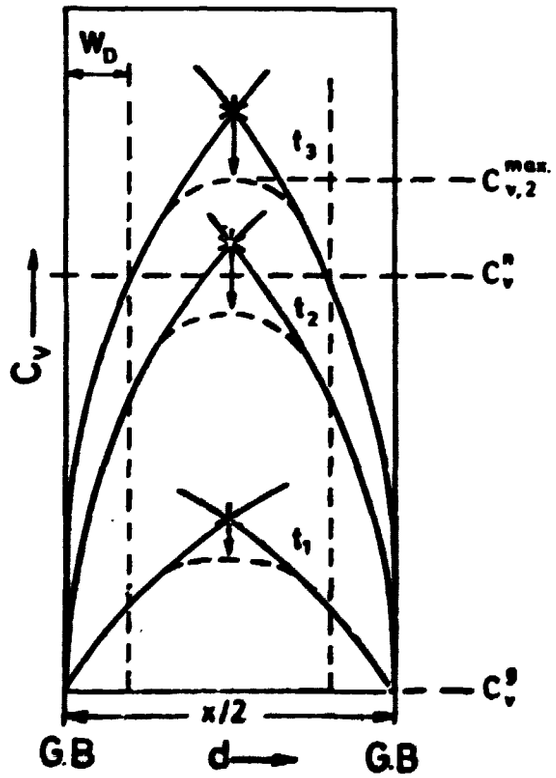


Fig. 8. Increasing vacancy concentration, C_v, with irradiation time, t_1 ($t_1 < t_2 < t_3$), and its variation with distance, d, from the grain boundary for $d_g = x$ and for $d_g = x/2$. C_v^g = equilibrium vacancy concentration in the grain boundary, C_v^n = vacancy concentration necessary for the nucleation of voids to occur, C_v^{max} = maximum vacancy concentration achieved.

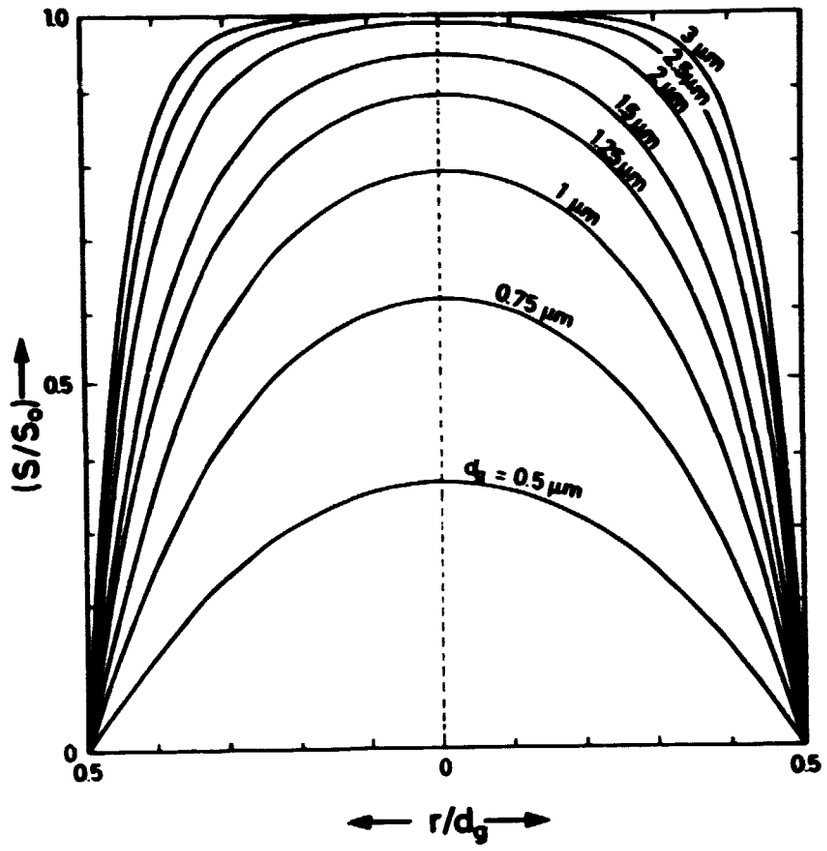


Fig. 9. Vacancy supersaturation profiles calculated for different grain sizes; here f and $(\alpha\, d_g^2)^2$ are calculated for our material under electron irradiation at 600°C (see text).

Fig. 9 shows the effect of grain size on the calculated vacancy supersaturation profiles within the grains. The fact that the vacancy supersaturation level in a 2.50 μm grain (at $r/d_g = 0$, where r = radial distance from the centre of the grain to the grain boundary) approaches its bulk value, would suggest that in grains with $d_g \geq 2.50$ μm the effect of grain size on void formation and growth (through vacancy depletion from the grain interior) should be negligible. The above prediction is borne out by our experimental results which showed that the void volume swelling in 2.60 μm grains (without helium) and 2.77 μm grains (with 10 ppm helium) was much the same as in type 316 stainless steel with $d_g \sim 50$ μm.

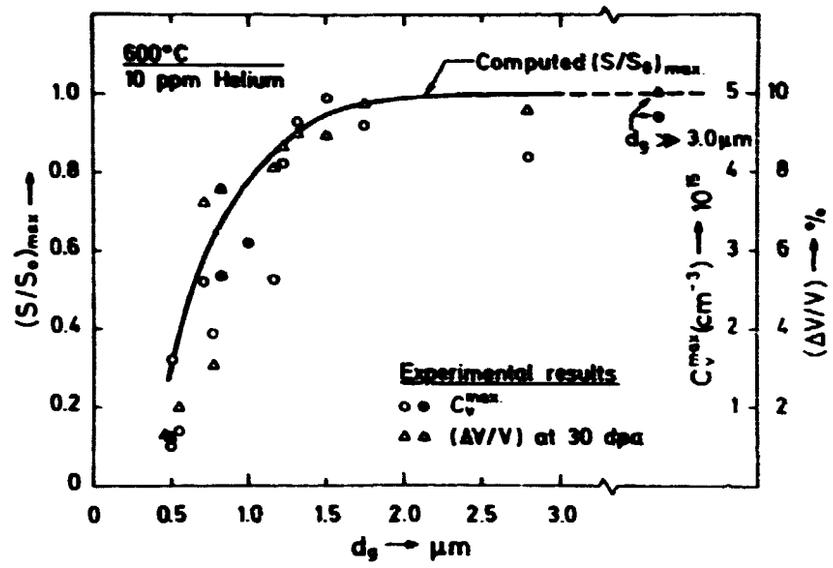


Fig. 10. Variation of $(S/S_0)_{max}$, C_v^{max}, and (ΔV/V) at 30 dpa with the size of the irradiated grain; $(S/S_0)_{max}$ is the value of (S/S_0) at $r/d_g = 0$ in fig. 9, C_v^{max} and (ΔV/V) are measured values of void number density and void volume swelling respectively, in the centre of the grain. Open and closed symbols refer to foil thicknesses of about 0.5 μm and 0.8 μm respectively.

The maximum value of vacancy supersaturation in the centre of all the grains (i.e. at $r/d_g = 0$) mentioned in fig. 9 is plotted against grain size in fig. 10. Fig. 10 also includes the maximum void number density and void volume swelling measured in the centre of grains of various sizes; the foil thicknesses used were about 0.5 μm (open symbols) and 0.8 μm (closed symbols). These results clearly demonstrate that the experimentally measured dependences of the maximum void number density and the void volume swelling on grain size are very similar to that of the calculated vacancy supersaturation on grain size in the whole grain size range investigated.

Conclusions

Our investigation showed that in both undoped and helium-doped stainless-steel samples, void nucleation (as observed in the microscope) is delayed, void concentration lowered, and void volume swelling reduced by grain refinement and a dispersion of second-phase particles. The grain size effect can be explained in terms of a "defect depletion model"; the model is supported by our calculations of vacancy supersaturation profiles in three-dimensional grains. Our work suggests that void nucleation is strongly influenced by the level of vacancy supersaturation and that the grain size effect is controlled predominantly by the nucleation process.

A NEW SYSTEM FOR AUTOMATIC TUBE INSPECTION

H. E. Gundtoft and C. C. Agerup

An advanced system (fig. 11) for the non-destructive control of fuel cladding tubes for nuclear reactors has been developed and tested at Risø during the last few years. The system has also been on trial under normal production conditions at Sandviken's cladding tube factory in Sweden. Production and sales rights have now been taken over by The Elsinore Shipbuilding and Engineering Co., Ltd.

One type of fuel used in nuclear reactors is uranium dioxide in the shape of small pellets encapsulated in tubes; the pellets usually have diameters in the range 9 - 13 mm. For water-cooled reactors the cladding tubes are normally fabricated from a zirconium alloy which has a very low neutron absorption cross section. In order to improve the neutron economy even further it is desirable to use as little material as possible. On the other hand, sufficient strength of the cladding tubes must be ensured. Additionally, the gap between the pellets and the containing tube must lie within close tolerance limits in order to achieve optimum heat transfer characteristics. The fulfilment of these various and stringent requirements can only be achieved if the tubes are produced defect-free and to very exact dimensional specifications (inner and outer diameter and wall thickness). Table 2 shows a typical example of such a specification. To ensure that the tubes fulfil these strict dimensional and quality requirements, it is necessary that they undergo a thorough inspection which must be both reliable and fast.

Fig. 11. The tube inspection system developed at Risø.

Table 2

Tube inspection specifications

Type of Inspection	Parameter to be checked	Dimensional limits or inspection requirements
Dimensional Control	Internal diameter Wall thickness Outer diameter	12.670 ± 0.040 mm 0.810 ± 0.080 mm 14.290 ± 0.040 mm
Defect Inspection	Longitudinal defects in tube wall Transverse defects in tube wall	Standard defects are used for calibration Min. length = 2.5 mm Depth 10% of the wall thickness Min. depth 0.050 mm, in longitudinal and transverse directions outside and inside the tube

Current Inspection Methods

There are a limited number of systems currently in use for the non-destructive examination of fuel cladding. For routine inspection in production the most modern of these requires two separate benches. One bench is used for defect inspection and wall thickness measurement, the data being obtained in one pass of the tube, whilst the other bench is used to determine external and internal diameter. For the latter operation a probe, which is attached to a long arm, has to be passed along the bore of the tube.

In both of these benches the tubes are rotated and translated by means of rubber wheels, and the scanning follows a helical path. The normal rotation speed for defect testing is about 1000 rpm, but for internal diameter measurement a rotation speed not exceeding 300 rpm is used in order to guarantee sufficient accuracy. This disparity between the rotation speeds of the two benches means that in order to obtain the same capacity for the two benches - a necessary condition if they are arranged in series in a control line - the pitch of the helical path must be increased in the second bench; this leads to a concomitant reduction in the effectivity of the inspection.

For 100% control, i. e., control of all tubes along their entire length, the capacity of such a control line with two benches in series is approximately 250 km of tubes per year.

The New Inspection System

The inspection speed of the advanced system which we have developed

is more than twice that obtainable with the two-bench system mentioned above. This improvement has been partly achieved by eliminating the time-consuming measurement of internal diameter with an internal measurement probe. In the new system the external diameter and the wall thickness are measured in a rotating measurement chamber (3000 rpm), through which the tube is passed without rotation. Since the measurements of outer diameter and wall thickness are, in our system, directly related to one another, the internal diameter can easily be determined as the difference between these two measurements. In addition, the new method allows both defect control and dimensional measurement to be performed in one continuous operation: since the complete inspection system is contained in one single measuring bench, the new technique obviates the necessity for two benches in series. The actual measurements are performed by means of the ultrasonic impulse echo method, which completely eliminates all contact between the tube and the measuring instrument; the rotating measurement chamber means that, even at very high measuring speeds, the tube can easily be passed through the control unit. Even though the measuring speed is higher than in conventional benches, the movement of the tube surface relative to the guidance is much slower by our rotationless feed. This results in a more gentle handling of the tube.

The recorded data are processed by a computer coupled to the system. This gives significant advantages during production control since the computer can be programmed with the required tolerance limits of the various dimensional and defect measurements. Provided the results lie within these limits the tube is accepted and inspection continues automatically: if a value lying outside the specification is recorded, two options are available; inspection can either be discontinued to allow immediate closer examination of the offending result, or the tube concerned can be rejected and stored for further careful examination at a later date.

The use of a computer also permits easy recording and statistical processing of the results; it is thus possible to avoid the time-consuming interpretation of the long and unmanageable strip charts produced by conventional measuring benches. The coupling of a traditional (analog) data recording system to the new bench is of course also possible.

Measurement Techniques

The following section considers in detail some of the individual parts of the new inspection system. The rotating measurement chamber is shown in fig. 12; fig. 13 shows the construction of the unit used for dimensional measurements, which, as mentioned previously, is based on the impulse

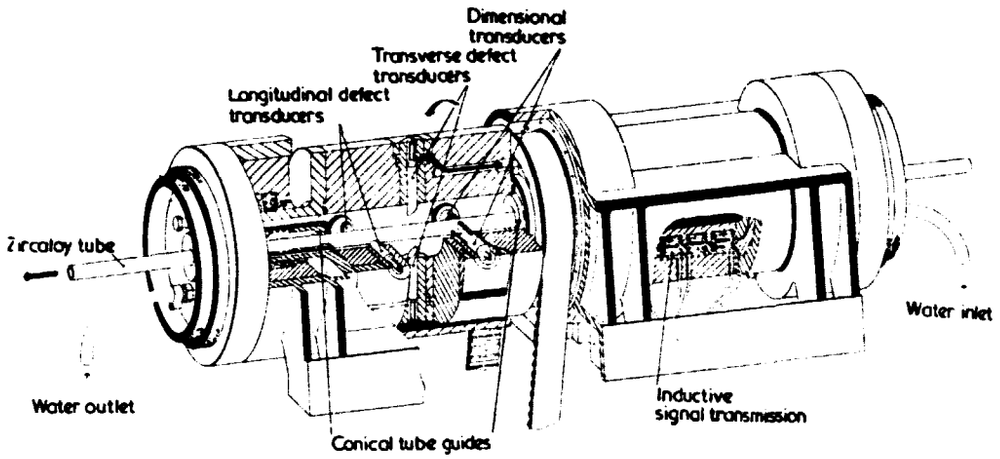


Fig. 12. Rotating test chamber.

echo method. The rotating measurement chamber is water-filled, and in order to minimize the distances over which the measurements are to be made, reflectors in the shape of fine wires are placed as close to the tube

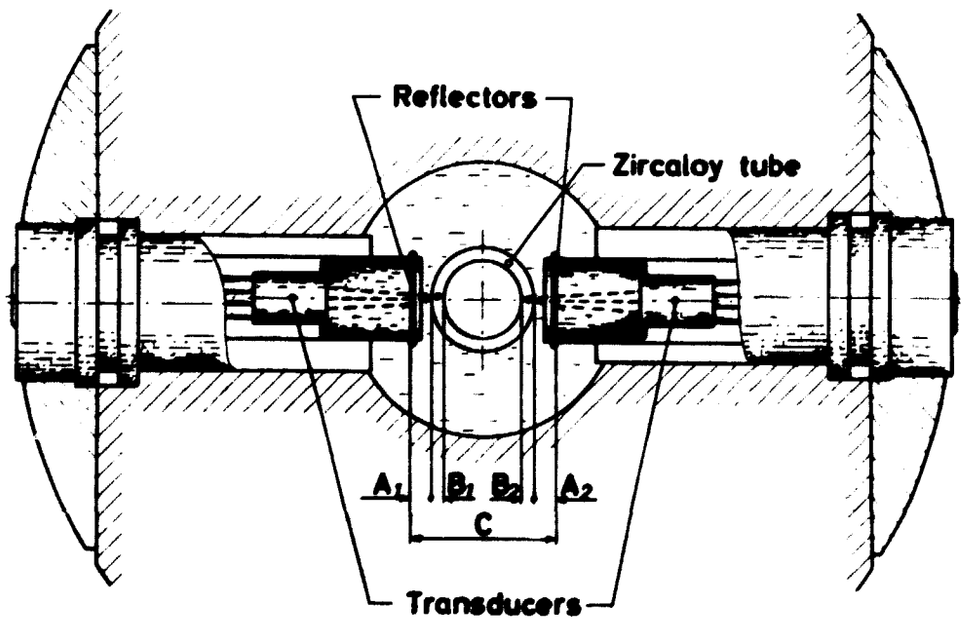


Fig. 13. Principle of dimension measurement. The measurement is performed in the water-filled central part of the rotating chamber.

as possible. Using ultrasonic pulses the distances A_1, A_2, B_1, and B_2 are measured; C is of course constant. The inner and outer diameters are calculated and recorded either by the computer or the analog unit; the wall thickness is given directly by B_1 and B_2. This method gives actual values of the dimensions rather than average values.

The effect of temperature on the velocity of sound through water is so great that large inaccuracies can be introduced into the diameter determination if the water temperature variations are not considered.

In order to achieve the desired accuracy the reflectors are placed immediately adjacent to the tube. In addition, the water temperature is held constant to within a few degrees; this is ensured by means of a closed circulation system containing a cooling unit which removes any heat generated during measurement. Finally, a compensator corrects the measurements for small variations in water temperature. Fig. 14 shows the efficiency of this compensator.

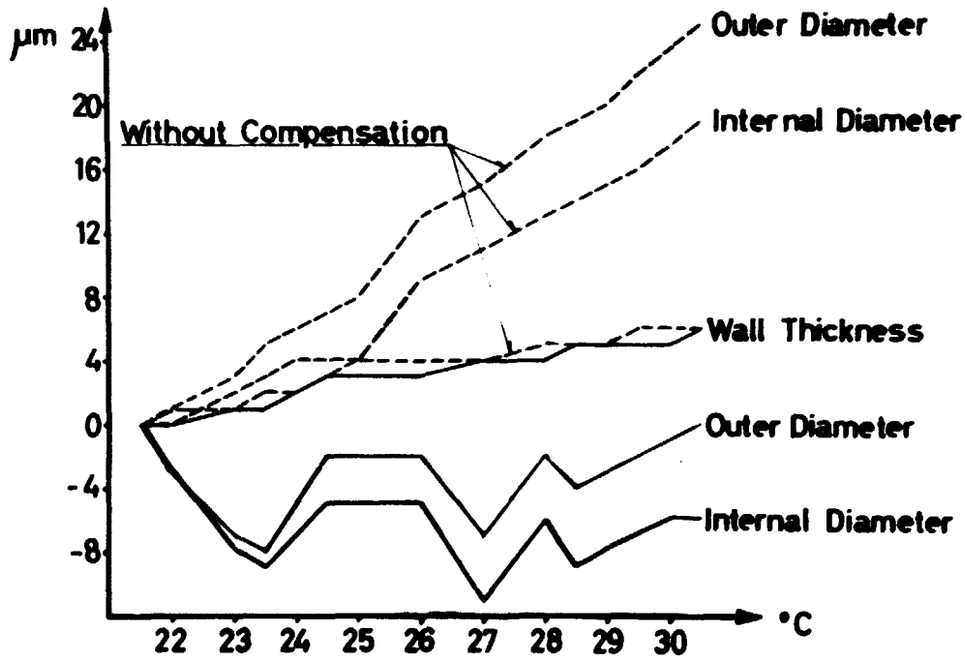


Fig. 14. Variation in dimension measurements with and without the temperature-compensating system in function.

The detection of defects is also accomplished by using the impulse echo method. As shown in fig. 12, two pairs of ultrasonic transducers are employed, one for detecting longitudinal and one for detecting transverse

defects. Two transducers are required for each defect type in order to guarantee detection of cracks inclined to the surface.

Tube Guidance System and Calibration

During the development of the inspection system, it became obvious that, for the precise measurement of diameter and especially for defect inspection, it is absolutely necessary to position the transducers accurately with respect to the tube. A precise guiding system was therefore developed. A contactless system being preferable, initial experimental work was aimed at producing a hydrodynamic bearing with the water in the system as the lubricating fluid. However, the required accuracy could not be obtained by this method. Therefore the system of conical plastic supports and springs illustrated in fig. 15 was developed. This arrangement guides the tubes exactly and has the additional advantage of being able to handle tubes of various sizes. It has been demonstrated that the guides do not damage the tubes.

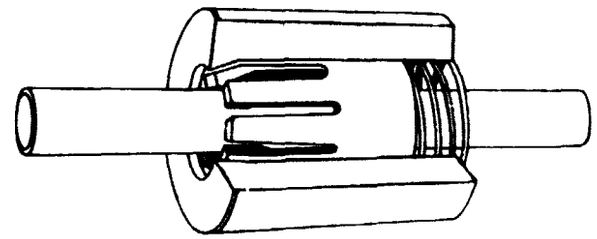


Fig. 15. Conical tube guide.

The system is capable of handling tubes with outer diameters in the range 10 - 20 mm. The transducers can be turned and moved radially within their holders. These degrees of freedom facilitate the optimum positioning of the transducers, which is necessary for the examination of tubes of different dimensions. Calibration is performed by means of a standard tube consisting of sections with various known diameters and containing artificial defects of known dimensions.

During calibration the chamber is rotated first by hand and then at the maximum speed of 3000 rpm. Calibration at 3000 rpm is possible because the synchronization of the ultrasonic equipment is controlled from the chamber; thus, it is possible to "freeze" any one of the artificial defects so as to produce the optimum echo by moving the tube.

Applications and Advantages

In a production line the measuring bench is capable of meeting most of the requirements of a tube manufacturer, viz. capacity, measuring range, measurement accuracy. In addition the recording system is ideally suited for computer handling and statistical analysis of the results, and furthermore the improved precision in the assessment of the tube could lead to relaxation of tube specifications and a concomitant reduction in rejection rate. Many of these advantages also increase the number of possible applications of the bench in research and development laboratories.

Since a more thorough analysis of the tube geometry is possible with the new measuring technique, the bench becomes particularly useful in the fuel element production industry. In this connection it can be mentioned that cladding for fast-reactor fuel has such a small bore (5 - 6 mm) that it is difficult, if not impossible, to use internal probes; thus, the new bench offers the only possible technique for controlling the internal diameter of such tubes.

Outside the nuclear field the system can be used for the control and inspection of any precision tube, e. g. heat exchanger and super-heat tubes. Often the length of tubes involved, typically 30 - 50 m, precludes rotation of the tube and the use of internal probes. In such instances the advantages of a rotating measuring chamber immediately become apparent.

PARTICIPATION IN INTERNATIONAL COLLABORATION

The department is engaged in the following types of international collaboration: joint technical projects, committee work, reception of research fellows, and technical and scientific meetings.

Participation in the NEA reactor project at Halden was continued. Six Danish fuel elements are at the moment being tested under irradiation in the Halden reactor. Fuel elements irradiated at Halden were examined for one of the other signatories (Italy) in the Hot Cells at Risø.

Joint technical projects were continued on measurement of the thermal conductivity of uranium dioxide under irradiation, studies of the thermodynamic behaviour of uranium-dioxide/plutonium-dioxide mixtures, and irradiation in the DR 3 of zircaloy-clad uranium-dioxide/plutonium-dioxide fuel rods (with the AB Atomenergi, Sweden). Also the programme on dispersion-strengthened zirconium alloys (with the UKAEA) was continued. Together with the Atomic Energy of Canada Ltd. (AECL) experiments are being carried out to investigate the in-pile creep properties of these alloys. The joint programme on examination of advanced zirconium alloys for water reactors (with the UKAEA, AB Atomenergi, IFA, Norway and the Finnish AEC) was continued. The department took part in a joint Scandinavian Nordforsk project on fibre reinforcement, and in a Scandinavian working group on hot cell techniques.

The department participated in the Halden Programme Group (member: N. Hansen), in the Halden Project Working Group on Fuel (member: P. Knudsen), in the IAEA working group on "Engineering Aspects of Irradiation Embrittlement of Reactor Pressure Vessel Steels" (member: A. Nielsen), and in the following Technical Commissions of the IIW (International Institute of Welding): Commission I "Gas welding and allied processes", Sub-Commission A "Brazing and surfacing" (member: J. Christensen), Commission IX "Behaviour of metals subjected to welding", and Commission X "Residual stresses and stress relieving. Brittle fracture" (member: A. Nielsen).

Furthermore the department was represented in the CREST (Committee of Reactor Safety Techniques of the NEA) working group: "Material and mechanical problems related to the safety aspects of steel components in nuclear plants" (member: A. Nielsen). N. Hansen and H. Lilholt were members of the Euratom Consultative Committees on Programme Management on "Plutonium and Transplutonium Elements" and "Solid State Physics" respectively. O. Toft Sørensen was a member of the council of the International Confederation of Thermal Analysis (ICTA).

EDUCATION AND TRAINING

Two members of the scientific staff of the department have been giving regular lectures on materials to students at the Danish Academy of Engineering. Two staff members acted as external examiners at graduate examinations.

In the department a number of students worked on studies in preparation for their bachelors theses. Four students from the Department of Mechanical Engineering of the Danish Academy of Engineering worked on the following projects:

"Crack Opening Displacement Measurements"

"Recrystallization of Aluminium/Alumina Alloys"

"Tensile Properties of Composite Materials with Long Parallel Fibres".

Four post-graduate students from the Technical University of Denmark worked in the department; one, from the Department of Structural Properties of Materials, finished work on his thesis:

"Additive Strengthening Mechanisms in Dispersion-Strengthened Products",

and two others from the same department worked on their theses

"Interactions between Grain Boundaries and Dislocations",

and "Creep of Fibre Composites".

The fourth student from the Department of Mechanical Technology started work on his thesis "Fracture Mechanics".

Two holders of scholarships from India have worked on projects within the areas of physical metallurgy and post-irradiation examination.

The following lectures were given by scientists visiting the department:

"The Modern Developments and Perspectives of Resistance Sintering" (T. Sakai, Japan)

"Chemomechanical Effects" (Norman Macmillan, U.S.A.)

"Microstructure and Fracture of Nb-Hf-Alloys and Ta-W-Hf-Alloys, (R. Carpenter, U.S.A.)

"Irradiation Damage in Metals" (B. L. Eyre, U.K.)

"Research on Fibre Composites at the École des Mines" (K. Street, France)

"Isotope Effects in Diffusion" (S. J. Rothmann, U.S.A.)

"Recrystallization" (R. W. Cahn, U.K.)

"Growth of Strong Microstructures for Elevated Temperature Applications" (G. J. Davies, U.K.).

PUBLICATIONS

Metallurgy Department Progress Report for the Period 1 April 1971 to 31 December 1972.

Risø Report No. 274 (1973) 48 pp.

Secondary Creep of Polycrystalline Magnesium Oxide.

J. B. Bilde-Sørensen, In: Proceedings of the Third Nordic High Temperature Symposium, held at Risø, 7-9 June 1972. Edited by Jens Gert Rasmussen. Vol. 1 (Polyteknisk Forlag, København, 1973) 119-132.

The abstract appeared in the previous progress report.

Dislocation Link Length Distribution in Creep-Deformed Magnesium Oxide.

J. B. Bilde-Sørensen, Acta Met. 21 (1973) 1495-1501.

A method for measurement of dislocation link length distribution (i. e. distribution of spacings between connected nodes) from transmission electron micrographs is given. The method is based on measurements of projected lengths of all links fully situated in the foil. By statistical corrections this two-dimensional distribution is converted to a three-dimensional distribution. The method has been applied to specimens of creep-deformed, polycrystalline MgO and an empirical equation for the distribution has been found. Also the influence of non-uniformity of the Frank network on the magnitude of β in the equation $L_{av} = \beta/\sqrt{\rho}$ is considered.

Dispersion Strengthening at High Temperatures.

A. H. Clauer, In: Proceedings of the Third Nordic High Temperature Symposium, held at Risø, 7-9 June 1972. Edited by Jens Gert Rasmussen. Vol. 1 (Polyteknisk Forlag, København, 1973) 133-171.

The abstract appeared in the previous progress report.

Entropy of fcc and hcp Lattices: Comparison of H Theorem Method with Vibrational Analysis.

P. O. Esbjørn, E. J. Jensen, W. D. Kristensen, J. W. Martin, and L. B. Pedersen, J. Comput. Phys. 12 (1973) 289-307.

The entropy of a Lennard-Jones model solid was calculated as a function of temperature, for both fcc and hcp phases, using data derived

from a molecular dynamics computer simulation. Two independent methods of calculation were used, one based on the Boltzmann H theorem and the other on the power spectrum method of Dickey and Paskin.

The Efficiency of Void Formation During Annealing of Irradiated Molybdenum.

J. H. Evans, Risø-M-1641 (1973) 9 pp.

Results are presented to demonstrate the high efficiency of vacancy retention that occurs when voids are formed by the annealing at 900°C of molybdenum samples neutron irradiated at 60°C. In the particular case examined the efficiency is shown to be some 50 times more than the theoretical maximum expected during the formation of voids under conventional high temperature neutron irradiation. Various aspects of this efficiency are discussed with particular reference to a recent positron annihilation study of the processes taking place during annealing. A mechanism for the high vacancy retention is suggested that depends largely on the storage of vacancies in loop form during irradiation below the temperature of vacancy loop shrinkage and the transfer of vacancies to voids on annealing above this temperature. There seems to be only a small possibility that the mechanism could operate unintentionally in reactor situations. On the other hand by ensuring void nucleation the high efficiency of void production by the irradiation-annealing method might be used to advantage in providing inexpensive void samples for experimental purposes. Finally, it is noticed in passing that the behaviour of the vacancy loops could provide a simple explanation of the empirical 0.3 T_m threshold for conventional void formation in metals.

Comments on Stage III and Stage IV Annealing mechanisms in Molybdenum.

J. H. Evans, Risø-M-1663 (1973) 14 pp.

Recent work on molybdenum giving evidence for interstitial and vacancy migration in stages III and IV respectively has been critically examined. Although the suggested annealing scheme is attractive, it is demonstrated that the evidence does not quantitatively support such a model. Alternatively it is argued that other investigations including recent positron annihilation studies point strongly to vacancy migration in stage III. In addition it is proposed that stage IV after neutron irradiation is due to the migration of some small vacancy cluster, possibly the trivacancy or tetravacancy.

The Efficiency of Void Formation During Annealing of Irradiated Molybdenum.

J. H. Evans, Phil. Mag. 28 (1973) 1405-1408.

Results are presented which show that when voids are formed by annealing molybdenum at 900°C after neutron irradiation at 60°C, vacancies are retained with an efficiency about fifty times greater than the maximum possible when the material is irradiated at high temperatures. This high efficiency is considered in the light of recent positron annihilation studies of annealing in irradiated molybdenum by Petersen, Thrane and Cotterill (1973), and is thought to be due to the storage of vacancies in loop form below the temperature of vacancy loop shrinkage, and their transfer to voids on annealing above this temperature. The possible relevance to reactor situations and the 0.3 T_m threshold are discussed.

Fast and Accurate Non-Destructive Testing System for Inspection of Canning Tubes.

H. E. Gundtoft and N. Nielsen, Non-Destruct. Test. 6 (1973) 34-37.

The authors describe the development of an inspection bench for the non-destructive examination of canning tubes. The bench is original in that the internal diameter is calculated from exact measurement of the outer diameter and the wall thickness. The transducers for inspection and control are rotated around the tube. Thus all measurements are made externally to the tube. The result of these innovations is that non-destructive examination can be made in a single pass of the tube, and the assessment is more accurate, economical, and faster than that possible with existing techniques.

Dispersion Strengthening at High Temperatures in Al-Al_2O_3 Alloys.

N. Hansen and A. H. Clauer, In: Microstructure and Design of Alloys. Proceedings of the 3rd International Conference on the Strength of Metals and Alloys, Cambridge, 20-25 August 1973. Vol. 1 (Institute of Metals, London, 1973) 321-325.

The amount of particle strengthening during high temperature creep has been investigated in Al-Al_2O_3 alloys having coarse elongated grains. Four alloys containing different volume fractions of Al_2O_3 were fabricated from atomized aluminum powder. The alloys contained 0.2, 0.45, 0.8 and 0.9 vol.% oxide. The tensile properties

were measured in the temperature range -196°C to 600°C. Creep properties were determined at 300, 400, 500 and 600°C. The modulus compensated flow stress is highest below room temperature and falls to a lower, temperature independent level above room temperature. The creep strength decreases slowly with temperature at very high temperatures. It is concluded that the presence of stable, finely dispersed particles requires a flow stress which is relatively insensitive to temperature and strain rate, and is a significant fraction of the Orowan stress for glide. This flow stress has the characteristics of a slightly temperature dependent threshold stress which is approached at very low strain rates in creep. In the alloys containing the highest oxide content and having the most uniform distribution of oxide particles, it appears that the threshold stress at temperatures as high as 600°C and a strain rate of 10^{-10} sec^{-1} is about one-half of the Orowan stress.

Bestrahlungsexperiment zur Überprüfung des Waltherschen Spannungsmodells an beschichteten Brennstoffteilchen.

H. Hougaard, K. Bongartz, E. Gyarmati, H. A. Schulze, R. Thiele, and J. Baier, Reaktortagung Karlsruhe, 10-13 April 1973 (Deutsches Atomforum, Bonn, 1973) 315-319.

H. Walther, SORIN, has established a mathematical model, which describes the stresses in the single layers of a multilayer coated particle being used in Helium cooled graphite moderated high temperature reactors. The aim of the model is to provide evidence on the mechanical behaviour during irradiation and predict the life time of a coated particle. The institutions the Dragon Project, England, Kernforschungsanlage Jülich, Germany, SORIN, Italy and KEMA, Netherlands, designed and carried out a joint experiment to test the stress model mentioned. The aim of the experiment was to test the model and to check the validity of the material data used as input. The experiment comprised 15 different particle/coating combinations each irradiated to three different burn-ups.

Verification of Stress Calculations for Coated Fuel Particles by a Specific Irradiation Experiment.

K. Bongartz and H. Hougaard, In: Preprints of the Second International Conference on Structural Mechanics in Reactor Technology, Bonn, 10-14 September 1973. Vol. 1, part C (1973) paper C 1/3, 6 pp.

A specific irradiation experiment has been performed to test a mathematical model for calculation of stresses in coating layers of fuel particles for a high-temperature reactor. The stresses which are induced mainly by the internal fission gas pressure and the fast dose induced dimensional changes of the coating material can lead to breakage of the PyC- and SiC-coating layers. The aim of the model is to provide evidence on the mechanical behaviour during irradiation and predict the lifetime (irradiation time until breakage) of a coated particle. An extensive irradiation experiment was carried out to provide an optimum of information under two different aspects: a) Does the model adequately describe all relevant mechanisms (i. e. interaction between different layers, creep, etc.)? b) Are the input data sufficiently correct? From post-irradiation calculations it appeared that the actual lifetime could be brought in a relatively good accordance with the model predictions by fitting only the fast dose induced creep of the PyC-coating. It was found that in the low dose region, where this experiment was carried out, instead of constant creep a transient creep must be assumed, which was simulated in the new calculations. Fifteen different particle types were each irradiated up to three different end-dose values. In a total of 45 combinations the agreement between calculations and actual results therefore had to be established. With a very few exceptions a good agreement between the predictions and the results of the irradiation appeared concerning the lifetime. Therefore the new and significant results of the experiment were that it is possible with adequate accuracy to predict the lifetime of coated particle fuel for high-temperature reactor use by aid of the stress model.

Analysis of Ridge Formation.

N. Kjær-Pedersen, Risø-M-1625 (1973) 15 pp.

A mathematical model is discussed, which analyses the elastic and plastic deformation of a tube under a specified local load applied axisymmetrically to the inner tube surface. The model accounts for anisotropic plastic properties of the materials. Creep behaviour during irradiation is described by Nichols's model. Numerical results have been obtained by means of a digital computer. A discussion of these results is given.

UO_2 Pellet Stack Shortening in a Boiling Water Reactor.

F. List and P. Knudsen, Nucl. Tech., 20 (1973) 103-108.

Fuel pins of UO_2-Zr were irradiated to a burnup of 5600 MWD/t UO_2

in the OECD Halden Boiling Water Reactor. As a result, the pellet stacks shortened by appr. 0.7%. A mathematical model, based on a ratcheting pellet movement resulting from mechanical fuel-cladding interaction during successive irradiation periods, accounted well for the observed decrease in length. Examination of the inside of the cladding at several axial locations confirmed the ratcheting mechanism and indicated no contribution to pellet-stack shortening from isotropic fuel densification.

Overpower Testing of UO_2-Zr Fuel Pins.

P. Knudsen, H.H. Hagen, and J. Stiff, Risø-M-1653 (1973) 10 pp.

UO_2-Zr BWR type fuel pins were irradiated to 21,000-22,000 MWD/t UO_2 and then overpower tested in special rig systems. In the first test with a single fuel pin, the heat load gradually decreased from 480 to 215 W/cm, while the burnup was accumulated. The heat load was then increased at 9%/min. to 265 W/cm and maintained at this value for 3 weeks without any indication of failure. At reactor shut-down, a small amount of fission gas activity was observed; however, later observations indicated that this was a result of previous surface contamination rather than cladding failure. Two fuel pins were irradiated in another test at heat loads decreasing from 560 to 350 W/cm. The level was then increased (similar to the test above) to 420 W/cm. After $3\frac{1}{2}$ hr. at the new power level, release of fission products was observed, and the fuel pin was unloaded. Hot-Cell examinations showed failure at a large ridge on that pin, which had the smallest fuel clad gap. The same pin also exhibited the largest local cladding deformations (ridges at pellet interfaces). The tentative conclusion is made that the combination of heat load level and small gap resulted in excessive fuel clad interaction at the 20% overpower, which caused failure of the cladding.

Computer Programs for Texture Simulation.

T. Leffers, Risø Report No. 283 (1973) 52 pp. + 35 pp.

A description is given of three computer programs (ROLTEX 2, ROLTEX 1, and HORS dOEUVRE) for the simulation of the plastic deformation in face-centred cubic polycrystals and the derived development of rolling texture. The description includes a variety of test examples demonstrating that the programs work correctly. The report does not deal with the actual results produced by the programs and the physical interpretation of these results.

Review of Creep Theories for Fibre Composites.

H. Lilholt, In: Proceedings of the Third Nordic High Temperature Symposium, held at Risø, 7-9 June 1972. Edited by Jens Gert Rasmussen. Vol. 1 (Polyteknisk Forlag, København, 1973) 189-209.

The abstract appeared in the previous progress report.

A Fibre Composite with Metallic Matrix for Use at High Temperatures - a NORDFORSK Project.

H. Lilholt, In: Proceedings of the Third Nordic High Temperature Symposium, held at Risø, 7-9 June 1972. Edited by Jens Gert Rasmussen. Vol. 2 (Polyteknisk Forlag, København, 1973) 175-176.

The abstract appeared in the previous progress report.

Matrix Properties in a Fibre Composite with Metallic Matrix.

H. Lilholt, In: Microstructure and Design of Alloys. Proceedings of the 3rd International Conference on the Strength of Metals and Alloys, Cambridge, 20-25 August 1973. Vol. 1 (Institute of Metals, London, 1973) 237-242.

An analysis of matrix properties in a fibre composite was carried out and showed that the stresses in the matrix were dependent on the size of free matrix volume in a way similar to a grain size effect.

Loddesamlingers Styrke. (The Strength of Brazed Joints).

Aa. Lystrup, Dansk Tekn. Tids. 97 No. 7-8 (1973) 1-4.

The results of tensile and shear strength measurements, performed according to DIN 8525 are presented graphically. From the curves it is apparent that the strength of the joint is dependent on the strength of the base material; the stronger the base material, the stronger the joint. The curves also show clearly that the strength of brazed joints is only slightly dependent on the width of the brazing zone if this lies in the range 0.08 - 0.20 mm; the highest strengths are achieved with zone widths from 0.1 - 0.15 mm.

IIW (International Institute of Welding) Årsmøde 1972, Toronto. (IIW Annual Meeting 1972, Toronto).

A. Nielsen, Dansk Tekn. Tids. 97 No. 1 (1973) 36-43.

A review of the organization, procedures and work undertaken by IIW with special reference to the Technical Commissions IX and X, "Be-

haviour of metals subjected to welding" and "Residual stresses and stress relieving. Brittle fracture". Special topics from the meeting are mentioned: The Houdremont lecture by G. Kullberg, Sweden on Some Aspects of the Influence of Low and High Heat Inputs in the Welding of Steels. Papers on the Implant test, on the AVG-chart used for defect size detection during ultrasonic testing, on the Reheat Cracking and on the Japanese BPW process for Electro Slag Welding of metals inclined to brittleness in the heat affected zone.

Acoustic Emission Surveillance Methods.

A. Nielsen, Risø Report No. 277 (1972) 30 pp.

This report was prepared for the Commission of European Communities - Nuclear Energy Agency (NEA - CREST) working group on Material and Mechanical Problems Related to the Safety Aspects of Steel Components in Nuclear Plants. The report is based on information received recently from fruitful collaboration within the Working Group, from the literature, and from personal experience and communications. The purpose is to present the status of the acoustic emission technique with respect to its application during proof testing, recurrent testing and service, of steel pressure vessels for nuclear plants. During proof testing it is evident that the location of acoustic emission sources can be carried out very reliably. The problem of warning against catastrophic failure cannot at present be given a clear answer, although an experienced operator can make an approach to the problem and very promising investigations are in progress. During recurrent inspection it should be possible to gain further information on the state of the steel structure by applying the acoustic emission technique if the structure is accessible. Not much experience has been gained of acoustic emission surveillance during service in terms of Signature Analysis, but very promising investigations are in progress to solve the various problems, by using the acoustic emission technique in the hostile environment of a nuclear reactor.

Irradiation Embrittlement of Pressure Vessel Steels. IAEA Research Agreement No. 1071/CF.

A. Nielsen and J. Westermann, Risø-M-1634 (1973) 24 pp.

A Standard Research Programme was approved by the Coordinating Meeting on the 12th of May 1971 of the Working Group covering Engineering Aspects of Irradiation Embrittlement of Pressure Vessel Steels.

This Working Group was set up by the International Atomic Energy Agency. Several institutes in different countries agreed on doing irradiation experiments according to the approved programme on steel A 533B from the American HSST programme. The Danish contribution covering tensile, impact, and hardness testing of non-irradiated steel and steel irradiated at 290°C to 2×10^{19} n_f/cm^2 is presented in this report.

Computer Studies of Perfect Crystal Properties and Defect Structures in Ice I.

R. M. J. Cotterill, J. W. Martin, O. V. Nielsen, and O. Bøcker Pedersen, In: Proceedings of the International Symposium on Physics and Chemistry of Ice, held in Ottawa, 14-18 August 1972. Edited by E. Whalley, S. J. Jones, and L. W. Gold. (The Royal Society of Canada, Ottawa, 1973) 4.1.

An ice I model, containing two unit cells, and made infinite by use of periodic boundary conditions, has been studied by computer simulation. The individual molecules in the model interacted with one another through the effective pair potential of Ben-Nain and Stillinger which comprises contributions from electrostatic interactions, short-range repulsion and hydrogen bonding. By subjecting the model to small strains, values for the elastic stiffnesses were obtained which are in good agreement with experiment. Energies and the relaxed molecular configurations of several point defects were obtained by the method of molecular dynamics.

Inhibited Void Formation in Dispersion Hardened Austenitic Stainless Steel during High Energy Electron Irradiation.

B. N. Singh, J. Nucl. Mater. 46 (1973) 99-102.

Thin films of an "experimental" austenitic stainless steel with and without dispersions of alumina particles are irradiated in a High Voltage Electron Microscope. Irradiation experiments are carried out with 1 MeV electrons at 600°C. It is observed that the "experimental" stainless steels are considerably less prone to voidage than solution treated AISI type 316 stainless steel. It is suggested that the fine grain size and the presence of dispersed particles in the "experimental" stainless steel might be the cause of its resistance to void formation.

Void Volume Swelling Dependent on Grain Size in an Austenitic Stainless Steel.

B. N. Singh, Nature (Phys. Sci.) 244 (1973) 142.

Irradiation tests on sintered 20Ni/20Cr stainless steel both with and without alumina particles have shown that void concentration and void volume swelling are substantially reduced by decreasing the grain size. The presence of alumina particles makes an additional contribution to the grain-size effect by reducing the void volume swelling.

A Study of Irradiation Induced Voids in Dispersion Hardened Stainless Steel.

B. N. Singh, Risø Report No. 287 (1973) 43 pp.

An "experimental" stainless steel with ultra-fine grains and with and without dispersions of fine oxide particles has been irradiated with 1 MeV electrons in a High Voltage Electron Microscope; samples with and without implanted Helium have been irradiated. It is shown that the nucleation of voids and the resultant volume swelling are severely reduced by decreasing the size of the grain under irradiation. A further reduction in swelling is obtained in the specimens containing dispersions of oxide particles. The implanted helium atoms increase the void number density in large grains but have very little effect in the small ones. The present results are found to be consistent with a model based on the migration of point defects to grain boundaries giving rise to a grain size dependent vacancy concentration in the grain interior within a certain grain size range. It is concluded that the grain refinement and dispersion of small particles lead to a highly swelling resistant material which may be considered as an attractive candidate material for the fast breeder reactor application.

Grain Size Dependent Vacancy Supersaturation Profiles and their Influence on Void Formation in an Austenitic Stainless Steel during 1 MeV Electron Irradiation.

B. N. Singh and A. J. E. Foreman, Risø-M-1679 (1973) 19 pp.

In order to study the effect of grain size on void formation during high energy electron irradiations, the steady-state point defect concentration and vacancy supersaturation profiles have been calculated for three-dimensional spherical grains up to three microns in size. In the calculations of vacancy supersaturation as a function of grain size, the effects of internal sink density and the dislocation preference for interstitial attraction have been included. The computations show that the

level of vacancy supersaturation achieved in a grain decreases with decreasing grain size. The grain size dependence of the maximum vacancy supersaturation in the centre of the grains is found to be very similar to the grain size dependence of the maximum void number density and void volume swelling measured in the central regions of the grains. This agreement reinforces the interpretation that the grain size effect is due primarily to the depletion of point defects from the grain interior. It is suggested that the void nucleation is strongly dependent on the level of vacancy supersaturation.

On the Influence of Grain Boundaries on Void Growth.

B. N. Singh, Phil. Mag. 28 (1973) 1409-1413.

Growth behaviour of four individual voids has been studied using 1 MeV electron irradiation in a High Voltage Electron Microscope. Direct evidence is presented to show that the growth rate of voids is reduced markedly as the distance between the growing voids and grain boundaries becomes smaller than the "defect depleted zone width". As soon as grain boundaries reach growing voids, the void growth is found to cease altogether. At a given damage rate a void isolated from grain boundaries and other voids is found to follow a growth law of the form $d_v \alpha t_t^{0.63}$ where d_v is the void size and t_i is the irradiation time.

Corrosion Behaviour of New Zirconium Alloys.

E. Tolksdorf, In: 5th European Congress of Corrosion, Paris, 24-28 September 1973. (European Federation of Corrosion, Frankfurt am Main 1973) 321-323.

Korrosion i Zr-legeringer. (Corrosion in Zr-Alloys).

E. Tolksdorf, In: Korrosion og overfladebehandling, Middelfart, 8-10 januar 1973. Redaktion: V. F. Buchwald og S. Munch Jensen (Dansk Metallurgisk Selskab, København, 1973) 106-113.

A Simple Approximation for the Stress Concentration Factor at the Equator of an Oblate Spheroidal Cavity.

M. R. Warren and S. I. Andersen, Int. J. Fract. 9 (1973) 225-227.

A simple approximate solution is presented for the stress concentration factor at the equator of, and parallel to the polar axis of, an oblately spheroidal cavity or crack subjected to uniaxial stress acting at infinity and parallel to the polar axis. The solution is compared to the

exact solution given by Neuber, and is shown to be sufficiently accurate for the majority of quantitative work. For a Poisson ratio of 0.3, typical of many common metals, the error is less than +1% for a shape ratio of 2 and even for a sphere does not exceed +1.5%.

LECTURES AND CONFERENCE CONTRIBUTIONS

IFA 136, An Irradiation Experiment.

G. Testa, C. Lepscky, K. Bryndum, and C. Bagger, Presented at the Enlarged Halden Program Group Meeting, Sanderstølen, March 1973. (Transcript available, 10 pp.).

The IFA-136 experiment consisted of three pelleted fuel pins and one vipac pin. It reached a burn-up of 11,600 MWD/t UO_2 after twenty-seven months in the HBWR and was unloaded because of failure indication by fission gas release. Mechanical testing of the cladding and metallography of fuel and cladding have been performed. A pellet pin had failed at the maximum flux position, and ingress of coolant had caused oxidation of the fuel and hydriding of the cladding. Two sunburst attacks were observed at the location of the highest fuel density of the vipac pin.

Fuel Column Shortening in Irradiated UO_2-Zr Fuel Pins.

F. List, K. Bryndum, and P. Knudsen, presented at the BNES-Conference on Nuclear Fuel Performance, London, October 1973. (Transcript available, 3 pp.).

Fuel column shortening in irradiated UO_2-Zr BWR-type fuel pins apparently resulted from fuel clad mechanical interaction during successive irradiation periods, and a model was set up accordingly. A cladding examination enabled the determination of local pellet displacements which agreed well with model predictions. Isotropic densification did not appear to play any significant role in the shortening process.

Lodning, Egenskaber og Processer. (Brazing and Soldering - Properties and Processes).

J. Christensen, presented at Ingeniørsammenslutningen, København, November 1973. (Not available).

Analysis of Exposure Factors Influencing the Image Quality in Linear Accelerator Radiography.

J. Domanus and A. Jensen, presented at the Seventh International Conference on Nondestructive Testing, Warsaw, June 1973. (Transcript available, 6 pp.).

After a brief description of the Risø 10 MeV linear accelerator, exposure conditions for 50 to 250 mm steel plates are given. Kodak M and Agfa-Gevaert D2 and D4 films were used with lead, copper and fluorometallic screens. A slotted steel wedge defectometer was used to determine radiographic damage content and wire IQI's to determine radiographic image quality. X-ray film characteristic curves and exposure charts for steel were produced. Best results were obtained with thick lead intensifying screens and finegrained X-ray films.

Computer Simulation of Dislocation Motion.

P. O. Esbjørn, T. Leffers, and R. M. J. Cotterill, presented at the Fifth Nordic Solid State Physics Conference, Gausdal, January 1973. (Not available).

A study has been made of the motion of a perfect dislocation in a two-dimensional hexagonal Lennard-Jones solid, using computer simulation by the molecular dynamics technique. The threshold value of applied stress required for dislocation motion was determined as a function of temperature and model size. For very low temperatures good agreement is obtained between the observed and theoretical values of the Peierls-Nabarro stress.

Results of Non-Destructive Examination of Tubes by Means of a New Inspection System.

H. E. Gundtoft, N. Nielsen, and C. C. Agerup, presented at the V International NDT Congress, Warsaw, June 1973. (Transcript available).

The outstanding feature of the system is that defect examination and all tube dimensional measurements are made externally to the tube by means of ultrasonic transducers, which are located in a rotating water chamber. All results are fed into a computer, which makes the necessary calculations. This paper explains the calibration of the system and the presentation of the results. Because the ultrasonic transducers are synchronized by the water chamber as it rotates, it has been possible to carry out measurements and inspections under identical conditions. The computer in the system has made possible the comparison of results from different test runs. The results are digitalised and statistical treatments have been made. On the basis of its economical and technical advantages the system is compared with conventional methods for the non-destructive examination of canning tubes for nuclear fuel elements. The use of the system is also discussed for any non-nuclear application, which involves the examination of tubing which has to be produced to close tolerances.

Vergleich von Methoden zur schnellen und genauen Messung von inneren Rohrdurchmessern.

H. E. Gundtoft, C. C. Agerup, and N. Nielsen, presented at Vortragstagung der Deutschen Gesellschaft für Zerstörungsfreie Prüfverfahren, Salzburg, October 1973. (Manuscript submitted to non-Destructive Testing).

Continuous measurement of the inner diameter of precision tubes with an air-gauge is without any value the way it is often carried out in practice. The inner diameter is measured by rotating the tube over the measuring gauge which is mounted at the end of a supporting tube. We improved the well-known air gauge technique for measurement of tubes by placing the pressure transducer close to the air nozzles. The measuring speed was thus increased to approx. 12 times that of the conventional air gauge. We also investigated the capacitive measuring method and found that it is stable, exact, and fast. To avoid a measuring probe introduced into the tube, we developed a system in which the inner diameter is determined indirectly by calculation from measurement of the outer diameter and the corresponding wall thicknesses. In the same system the tubes are also checked for defects. All measurements and examinations are made with ultrasound in a rotating water chamber, and the measuring speed is thus only limited by the speed of rotation of the chamber.

Analysis of Ridge Formation.

N. Kjær-Pedersen, presented at the Enlarged Halden Program Group Meeting, Sanderstølen, March 1973. (Available as Risø-M-1625).

A Model for Fuel Rod Mechanical and Thermal Behaviour.

N. Kjær-Pedersen, presented at the BNES Nuclear Fuel Performance Conference, London, October 1973. (Transcript available, 4 pp.).

A fast computational model for the description of fuel pellet and clad transient loading and interaction is presented. Material properties, geometry and space- and time-dependent power generation rate are input to the model which in turn calculates, for each point in time,

temperature profiles, state of stress and state of elastic and plastic deformation under the basic assumption of axisymmetry. Axial-radial shear stress is taken into account as is yielding of clad and anisotropic irradiation creep of both fuel and clad materials.

Pellet Stack Shortening in the Danish Fuel Assembly IFA 162 and the Mechanism Behind It.

F. List and P. Knudsen, presented at the Enlarged Halden Program Group Meeting, Sanderstølen, March 1973. (Transcript available, 12 pp.).

UO_2-Zr fuel pins were irradiated to a burn-up of 5,600 MWD/t UO_2 in the Halden Boiling Water Reactor. As a result, the pellet stacks shortened by about 0.7%. A mathematical model, based on a ratcheting pellet movement resulting from mechanical fuel-clad interaction during successive irradiation periods, accounted well for the observed length decrease. Examination of the inside of the cladding at several axial locations confirmed the ratcheting mechanism and indicated no contribution to pellet stack shortening from isotropic fuel densification.

Overpower Testing of UO_2-Zr Fuel Pins.

P. Knudsen, H. H. Hagen, and J. Stiff, presented at the CREST meeting on Safety of Water Reactor Fuel Elements, Paris 1973. (Available as Risø-M-1653).

A Kinematical Model for the Plastic Deformation of Polycrystals.

T. Leffers, presented at the Fifth Nordic Solid State Physics Conference, Gausdal, January 1973. (Not available).

A model is proposed for the plastic deformation of polycrystals; it is aimed particularly at describing the way in which the individual grains adjust their deformation to maintain material continuity. The model is kinematical in the sense that it only deals with the slip processes taking place during deformation - the magnitude of the stresses involved is not considered. The model is based on the textures (preferred orientations) and microstructures developed during rolling of face-centred cubic metals and alloys. The model is unique in the sense that it yields a semiquantitative explanation of the lattice bending developed in the individual grains as a result of the deformation.

Twinning and Texture.

T. Leffers and P. Kayworth, presented at the 3e Colloque Europeen sur les Textures et leurs Applications Industrielles, Pont-a-Mousson, June 1973. (Proceedings to be published).

Initially texture-free copper and brass (15% zinc by weight) is rolled to 40% reduction. The rolling textures are registered by neutron diffraction measurements, and the crystallography and morphology of the deformation twins formed in the rolled brass are investigated by transmission electron microscopy - with the aim of providing an experimental check of the twinning theory for the texture transition in face-centred cubic materials. The experimental results are found to differ from the deductions from the twinning theory. The conclusion is that the twinning theory does not give a satisfactory description of the processes leading to the development of the copper-type and the brass-type texture respectively (a conclusion that agrees with the results of earlier investigations). Therefore, there must be a - decisive - difference between the deformation modes leading to the respective textures other than the difference between no twinning and twinning.

Molecular Dynamics Simulation of Grain Boundary Formation.

R. M. J. Cotterill, T. Leffers, and H. Lilholt, presented at the Fifth Nordic Solid State Physics Conference, Gausdal, January 1973. (Not available).

The formation of grain boundaries in hexagonal two-dimensional Lennard-Jones solids has been studied by computer simulation. A liquid layer is generated between two mutually misoriented crystal faces and it is then allowed to freeze. The temporal evolution of the system is calculated by the molecular dynamics technique which involves digital solution of the classical equations of motion. Since this method produces not only configurations but also velocities the thermodynamic state of the system is known at every instant, and it can be adjusted. In the present studies the pressure was maintained at one atmosphere during the freezing by adjusting the positions of the crystal faces. The boundaries produced by this method are found to be approximately straight and they are fairly regular. The method also permits the study of boundary migration.

Spændings-Bøjningskurver, Trækforsøg. (Stress-Strain curves, Tensile Testing, fibre composites).

H. Lilholt, presented at the NORDFORSK Seminariedag om Fiberarmerede Metaller, Stockholm, November 1973. (Not available).

Tensile experiments at room temperature have been carried out and analysed; the fibre composites behave as expected; the bonding between fibres and matrix has been estimated, and is good for composites made by liquid infiltration.

Smelteinfiltration. (Liquid Infiltration, fibre composites).

H. Lilholt, presented at the NORDFORSK Seminariedag om Fiberarmerede Metaller, Stockholm, November 1973. (Not available).

Fabrication of fibre composites by liquid infiltration has been investigated; the system is nickel with tungsten wires and small specimens can be produced.

Krybning. (Creep, fibre composites).

H. Lilholt, presented at the NORDFORSK Seminariedag om Fiberarmerede Metaller, Stockholm, November 1973. (Not available).

Preliminary creep experiments at 800 and 900°C on Ni-W composites show properties comparable to other experimental composites and conventional superalloys.

Fiberforstærkede Materialer, Deres Egenskaber og Anvendelser. (Fibre-reinforced Materials, Their Properties and Applications).

H. Lilholt, presented to Dansk Metallurgisk Selskab, Lundtofte, November 1973. (Not available).

A description was given of the principles of fibre reinforcement concerning tensile properties, fracture behaviour, and creep properties; examples from metals, ceramics and plastics were used for demonstration of the ideas.

Akustisk Emission til Overvågning af Konstruktioner. (Acoustic Emission Surveillance of Steel Structures).

A. Nielsen, presented to Dansk Svejseteknisk Landsforening, January 1973. (Not available).

A review of the application of acoustic emission for surveillance with special reference to pressure vessels, followed by a demonstration of a simple location technique.

Brudmekanikkens Problematik og Forslag til Nye Modeller. (The Limits of Fracture Mechanics and New Models of Fracture).

A. Nielsen, presented to Sveriges Mekanförbund, Stockholm, June 1973. (Not available).

The plastic zone problem and possibilities for handling of the problem by distinguishing between deformation hardening by shearing or by contraction. A dynamic fracture model to handle the brittle fracture in a limited brittle volume surrounded by ductile metal.

Akustisk Emission til Overvågning af Tryktanke. (Acoustic Emission Surveillance of Pressure Vessels).

A. Nielsen, presented to Sveriges Mekanförbund, Stockholm, June 1973. (Not available).

A review of the experience gained so far within the subject.

Corrosion and Deuterium/Hydrogen Pick-up in the Danish Fuel Assembly IFA 162.

K. Rørbo, P. Knudsen, and K. Bryndum, presented at the Enlarged Halden Program Group Meeting, Sanderstølen, March 1973. (Transcript available, 13 pp.).

Fuel pins with unautoclaved and autoclaved Zircaloy cladding were irradiated for 220 days in the OECD Halden Boiling Water Reactor. Corrosion and deuterium/hydrogen pick-up were determined and compared with results from out-pile autoclaving in D_2O. No significant difference was observed between the different surface treatments. The levels of deuterium pick-up were high when compared with the hydrogen pick-up which occurs in commercial BWRs. The relative pick-up between deuterium and hydrogen showed a strong preference for hydrogen.

Nucleation and Growth of Defect Agglomerates in Stainless Steel During High Energy Electron Irradiation.

B. N. Singh, presented at the Fifth Nordic Solid State Physics Conference, Gausdal, January 1973. (Not available).

Thin foils of an austenitic stainless steel have been irradiated "in situ" with 1 MeV electrons in a High Voltage Electron Microscope at 600°C with a displacement rate of $\sim 5.16 \times 10^{-3}$ displacements per atom (dpa) per second. Defect clusters with black dot contrast were ob-

served to nucleate almost immediately after irradiation began; these black dots rapidly grew into resolvable unfaulted dislocation loops. At higher displacement doses, well defined voids were observed to nucleate which then grew, in general, with a decreasing rate. The nucleation, and growth of these defect agglomerates have been shown to depend critically on the density and distribution of defect sinks such as dislocations, second phase particles, and grain boundaries. The influence of impurity gas atoms, implanted before irradiation, on the stabilization of three dimensional vacancy cluster configurations which serve as void nuclei is also discussed.

Radiation Damage Study Using 1 MeV Electrons.

B. N. Singh, presented at the Symposium on Electron Microscopy in Physics, arranged by Selskabet for Faste Stoffers Fysik og Kemi, Lundtofte, March 1973. (Not available).

The study of irradiation induced damage at elevated temperatures has recently gathered momentum, primarily because of its direct relevance to the development of Fast Breeder Reactors. The most significant aspect of the elevated temperature radiation damage is the formation of voids, leading to dimensional instability and brittleness in most polycrystalline solids. Although the phenomenon of void swelling is reasonably well understood, very little is known about the void nucleation mechanism(s) and the role of the various structural parameters in the nucleation and growth of voids. There are several ways in which damage studies using high energy electrons can contribute to the present understanding of these processes; these will be discussed in detail. The possibilities will also be discussed of using high energy electron irradiation as a tool for studying several other problems related to the damage studies. It will be demonstrated that in most practical cases, high energy electron irradiation results obtained using thin foils are valid and reliable; limitations of the technique will also be considered. Finally, some selected results obtained using 1 MeV electrons will be presented and their scientific and technological significance will be discussed.

Analysis of the Effects of Dispersed Particles and Irradiation on the Deformation Behaviour of Zr-2.

B. N. Singh, M. R. Warren, and P. D. Parsons, presented at the BNES Nuclear Fuel Performance Conference, London, October 1973 (Transcript available, 3 pp.).

Irradiated and unirradiated Zr-2 specimens with and without dispersions of inert particles have been tensile tested at 250 and 350°C. The onset of premature work softening in irradiated alloys is postponed by the presence of particles. This is discussed in terms of the effects of irradiation induced defects and particles on dislocation mobility and structure. It is concluded that at 250°C the major effect stems from vacancy-dislocation interactions, whereas at 350°C the effects of dislocation loops and vacancy annealing assume more dominant roles.

Thermogravimetric Studies of the High Temperature Thermodynamic Properties of Plutonium Oxides.

O. Toft Sørensen, presented at the Second NORDFORSK Symposium on Thermal Analysis, Risø, September 1973. (Proceedings to be published).

Plutonium oxides are used as fuel material in power reactors. In order to choose the best fabrication conditions for these oxides, as well as to predict their behaviour in the reactor it is important to know their thermodynamic properties accurately over an extended temperature range. In the present paper, work on the determination of thermodynamic data by thermogravimetric measurements are reviewed for pure PuO_2 and for UO_2-20% PuO_2 mixed oxides in the temperature range 900 - 1500°C and in different atmospheres consisting of CO_2/CO mixtures. These measurements were carried out in an "active" thermobalance enclosed in a glove box system.

STAFF OF THE DEPARTMENT

(as at 31 December 1973)

N. Hansen (head of department)

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Eichen, A. M.
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Evans, J. [2]
Frederiksen, H.
Gundtoft, H. E.
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Jensen, A. [1]
Jensen, F.
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Knudsen, P.
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Rasmussen, A.
Rørbo, K.
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Strange, S.
Strauss, T.
Sørensen, O. Toft
Tolksdorf, E.
Vigeholm, B.
Warren, M. R.
Weiler-Madsen, B.

Of the 61 members of the department, 33 belong to the scientific staff, 24 to the technical staff, and 4 to the office staff.

1) On leave from the Elsinore Shipbuilding and Engineering Co., Ltd.

2) On leave of absence from the Department of Metallurgy, AERE, Harwell

3) Post-graduate student from the Technical University of Denmark

Consultants

Gas analysis	S. Kühnel Hagen
Welding	E. Ostergaard (Danish Welding Inst.)
Non-destructive Testing	N. Nielsen (Danish Welding Inst.)
Physical Metallurgy	R. M. J. Cotterill (Technical University of Denmark)